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# Practical methodology for the design and management of instability in hard rock tunnels

## Méthodologie pratique pour la conception et la gestion de l'instabilité dans les tunnels en roche dure

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**ABSTRACT:** The stability of rock faces in underground facilities is critical when considering their lifespan as well as the health and safety of the operatives working within them. Recent years have seen an evolution of new techniques for inspecting tunnel faces and options available to remediate instability - the Lidar technology is becoming more readily available and necessary for assessment of the stability of rock faces. However, rockbolts and sprayed concrete remain the most commonly used solutions within underground facilities in Scotland. These have to be suitably specified to ensure their required design life can be achieved and, as such, detailed site investigation must be carried out prior to their installation. Factors such as groundwater flows and chemical aggression are variables that can potentially be considered when specifying levels of corrosion protection for rockbolts or the drainage requirements of a sprayed concrete system prior to application. In order to ascertain the exact position or pattern of rockbolts, a classification and analysis and of the geological conditions on site has to be carried out to inform the design of a stabilisation system. Critical analysis showed that the majority of the engineering works associated with remediating instability in hard rock tunnels is based on engineering judgement rather than governing standards which makes it difficult for stakeholders to suitably manage problems with instability, and rely heavily on consultants for advice. In an attempt to address this, this study aims to provide the stakeholder's geotechnical engineers with a best practise methodology framework in dealing with instability in hard rock tunnels, critically reviewing the site investigation techniques used and following up the information flow and geotechnical data management through to the design stage.

**RÉSUMÉ:** La stabilité des parois rocheuses dans les installations souterraines est essentielle si l'on tient compte de leur durée de vie, ainsi que de la santé et de la sécurité des ouvriers qui les travaillent. Au cours des dernières années, de nouvelles techniques d'inspection des parois de tunnel et d'options permettant de remédier à l'instabilité ont été mises au point. La technologie Lidar devient de plus en plus facilement disponible et nécessaire pour évaluer la stabilité des parois rocheuses. Cependant, les boulons d'ancrage et le béton projeté restent les solutions les plus couramment utilisées dans les installations souterraines écossaises. Cependant, ceux-ci doivent être spécifiés de manière appropriée pour garantir la durée de vie requise pour la conception et, en tant que tels, une étude de site détaillée doit être effectuée avant leur installation. Des facteurs tels que les écoulements d'eaux souterraines et l'agression chimique sont des variables qui peuvent potentiellement être prises en compte lors de la spécification des niveaux de protection contre la corrosion pour les boulons d'ancrage ou des exigences de drainage d'un système de béton projeté avant l'application. Afin de déterminer la position ou le modèle exact des boulons d'ancrage, une classification et une analyse, ainsi que des conditions géologiques sur site, doivent

être effectuées pour éclairer la conception d'un système de stabilisation. Une analyse critique a montré que la majorité des travaux d'ingénierie liés à la correction de l'instabilité dans les tunnels en dur est basée sur le jugement d'un ingénieur plutôt que sur des normes en vigueur, ce qui complique la gestion des problèmes d'instabilité par les parties prenantes. sur des consultants pour des conseils. Pour tenter de résoudre ce problème, la présente étude vise à fournir aux ingénieurs géotechniques de la partie prenante une méthodologie de meilleures pratiques pour traiter l'instabilité dans les tunnels en pierre dure, en passant en revue de manière critique les techniques d'investigation du site utilisées et en assurant le suivi du flux d'informations et de la gestion des données géotechniques. Étape de conception.

**Keywords:** hard rock; tunneling; stability; shotcreting; anchorage; monitoring; inspection

## 1 INTRODUCTION

Recent times have seen advances being made in the drilling and blasting industry; chemical composition, explosive loading rates and mechanized charging. These have not only improved production rates but reduced blast induced damage thus increasing the lifespan and functionality of the underground facility. However, when considering the age of the underground facilities across the UK and the rest of the globe in many cases the benefits of these advances may not apply, as the facilities were constructed before the advances were used within the tunnelling industry.

Similarly, advances have been made in the technology used to map discontinuities in the rock tunnels, first through photogrammetry and more recently through point cloud technology. Although this resulted in a more accurate mapping and ultimately more safe design, the initial costs and the high level of computer power required to process the mapping data have limited their use.

Rockbolting is the most common form of rock stabilisation used today with rockbolts and rock dowels being the two most commonly used techniques in hard rock tunnels (Hoek, 1987). By looking at the shape and angle of the exposed planes of a block/wedge experienced engineers can judge the position and length of bolt required to stabilise a block/wedge at risk. The corrosion

protection of the bolt, which is one of the primary causes of failure (Hoek 2007), is covered by codes such as BS8081 but relies on engineering judgement and 'service conditions'.

Sprayed concrete or 'Shotcrete' (both wet or dry) is ideally applied at the time of excavation to stabilise it. This technique is commonly used as a remediation measure and as a method to increase the stability of an area of tunnel should it be required. Sprayed concrete can be combined with rock bolts or dowels to create a single, stable structural element. The selection between wet or dry mix shotcreting depends on the site conditions such as access (BASF, 2012) and cost. The design process with 'Shotcrete' is seen as 'imprecise' (CIRIA, 2009) and based on 'precedent experience and rule of thumb' (Hoek, 2007).

The aim of this study is to explore the current best practice methodology in managing instability in hard rock tunnels in Scotland. The objectives of this study will be to attain an understanding of current stabilisation systems in use in industry and the drivers behind their selection. Additionally, common causes of tunnel instability will be investigated together with the experience of inspection, design, construction, and monitoring of the stabilisation measures. Based on the above, a practical methodological framework for the design and management of instability in hard rock tunnels will be proposed.

## 2 METHODOLOGY

To achieve the aim and objectives of this study, a comprehensive critical literature review was carried out, followed by interviews with asset managers and consultants engaged in tunnel stabilisation at three case study locations (two in Scotland and one in Wales; Table 1). The interviews were designed to be semi-structured and focussed (Fellows and Liu, 2008) in order to illicit opinions on specific areas of the study such as typical instability causes, stabilisation solutions, experience with monitoring of the stability in hard rock tunnels, as well as potential ways of enhancing the design practice.

## 3 RESULTS AND ANALYSIS

### 3.1 Literature review

In hard rock conditions drill and blast techniques are the most common methods, offering versatility when considering the varying rock environments encountered (Heinio, 1999). Blast damage can extend several metres into rock which has been poorly blasted (Hoek, 2007); the halo of loosened rock can give rise to serious stability issues in the rock surrounding the underground openings. Scaling activities after blasting ensure unstable rock is fully removed, leaving the intact but damaged rock in place to relax and dilate over time (COWI, 2017). If careful blasting and correct scaling techniques are followed then this reduces the volume of rock support that will be required, this results in a stable tunnel at reduced costs (Hoek, 1987). Over-scaling can be detrimental to stability and, prior to scaling, geological mapping and discontinuity assessments should be undertaken (CIRIA, 2009)

The stability of a rock tunnel is dependent on the volume and orientation of the discontinuities that make up the block-like nature of the rock face. The blocks are very often dependent upon each other for support and the failure of one block or wedge could result in multiple block failures

along the tunnel (Chen, 1994). Ground water is capable of washing out the mineral infill and thereby reduces the friction between the blocks, increasing instability (NGI, 2015).

Current best practice in the process of managing instability in hard rock tunnels generally follows Hoek's (2007) guidance: site investigation to determine the dip and dip direction of the joint sets found is followed by identification of potentially unstable blocks. This is then followed by calculation of the factor of safety applicable to the blocks and calculation of the required rockbolts needed to raise the factor of safety to an acceptable level.

An important factor to consider when designing a stabilisation system including rock bolts is an appropriate level of corrosion protection. There are many factors that will affect the rate to which a steel bolt can corrode ground water composition, pH, flow rates, air temperature, applied stress, CO<sub>2</sub> content, metallurgy of the steel rock bolt as well as construction activities such as blast damage, quality of grout, and site handling or workmanship (Azis, et al., 2013; Saiang & Nordlund, 2008). Rock bolt corrosion can be counteracted by filling the gap between the bolt and the drill-hole wall with grout (Hoek, 2007) which appears to contradict BS 8081 which states that borehole grout does not constitute part of a protection system as the grout quality and integrity cannot be assured.

Rock classification systems (e.g. RMR and Q) have been updated to include sprayed concrete as a stabilisation methodology, but these updates are based upon empirical knowledge and, as such, rely on evidence of past use of sprayed concrete being successful rather than numerical data.

### 3.2 Interviews

The interviewees agreed that there appears to be some confusion in industry with regards to what is an acceptable level of corrosion protection for a rock bolt. The cause of this confusion may come down to interpretation of the BS 8081.

Clause 13.2.4.1 states that “designers should select corrosion protection systems appropriate to their assessment of service conditions”. To some this may be seen as a potential weakness in the standard as there is no definitive line that can’t be crossed but a reliance on engineering judgement. BS 8081 goes on to mention the use of cement grout as corrosion protection on numerous occasions 13.2.4.4.2 states that “certain materials, notably, epoxy or polyester resins, have the appropriate strength, ductility to withstand corrosion. They may be substituted for cement grout but are more expensive”.

The interviewees agreed that the experience of the Nozzle-Man is one of the most important factors when considering the quality of a sprayed concrete project which coincided with the industry view (Sprayed Concrete Association, 1999).

### 3.3 Case studies

The results of the literature review and interviews with the asset managers of the case study sites are summarised in Table 1. The tunnels at the case study locations were shown to have been constructed by drill and blast methods and are in use as part of either power generation facilities or mineral exploration. The causes of instability cover a representative range, including rock failures, groundwater, and also stabilisation measure failures. In terms of current practice of design and management of instability, visual inspections appear to be the main method of inspection, before scaling and/or non-destructive testing (NDT) is carried out. At one case study site a LIDAR inspection/survey was carried out and, in another, a corrosivity testing was carried out as part of this stage. Following these, a risk assessment is usually carried out (in two out of the three case studies), which then is followed by a numerical modelling and design of stabilisation measures (usually by a consultant). The drivers behind the selection of a stabilisation measure are varied, but usually include budget constraints and site-specific conditions (e.g. corrosive

environment or aging infrastructure). The range of stabilisation methods employed appears to be dominated by sprayed concrete and rockbolting which were recorded in all three case studies.

In terms of construction, the quality assurance for sprayed concrete generally follows the ISO 9000/14000 guidance although, the interviewees noted lack of detailed guidance /standardisation referring to sprayed concrete workmanship.

It is important to note that the interviewees had differing experiences with post-construction phases, with maintenance programme present at two of the three case study site and rock mapping used as a baseline for monitoring only noted at one case study site. Furthermore, one interviewee noted an issue with the quality and consistency of monitoring data which precludes comparable inspections and monitoring throughout the design life of the tunnel. Good maintenance and monitoring practice was noted at one case study site where cataloguing and record management of the stabilisation solutions were carried out.

## 4 DISCUSSION AND CONCLUSIONS

The first objective set was to attain an understanding of current stabilisation systems in use in industry and how they are selected. The main conclusion that I have drawn from this objective is that there are two driving factors which govern the selection process, the design life of the tunnel that requires stabilisation and the financial constraints of the tunnel owner. Good practice in managing the financial constraints was demonstrated at Case Study D site which is currently undergoing a full refurbishment of its stabilisation systems - this refurbishment was planned over an 8 year period starting in 2011, however due to station and budgetary constraints this period has been extended to 2020.

Table 1. Case study details

	Case Study C	Case Study D	Case Study G
<b>Tunnel construction method / dimensions</b>	Drill and blast, 6.5x4.5m	Drill and blast, variable	Drill and blast in granite, 6.5x4.5m
<b>Cause of instability</b>	No significant failure, discontinuity sets	Rock bolt failure, aggressive groundwater	Minor rock falls, groundwater intrusion
<b>Type of facility</b>	Power generation	Power generation	Quarry
<b>Total length of tunnels</b>	6 km	18 km	1.8 km
<b>Existing stabilisation</b>	Sprayed concrete, 20,000 rock bolts	Sprayed concrete, 15,000 rock bolts	Sprayed fibre reinf. concrete, rock bolts, steel ribs, sand bags
<b>Pre-design activity</b>	Visual inspection, scaling, MEWP, spec. for stabilisation, modelling	Visual inspection, NDT, groundwater corrosivity test, risk ass't	Visual inspection, NDT, LIDAR, scaling, risk ass't, modelling
<b>Adopted solution(s)</b>	Stainless steel bolts	Stainless steel bolts	Sprayed concrete, stainless steel bolts
<b>Design driver(s)</b>	Risk of aggressive groundwater and bolts past design life, visible blast damage, maintenance programme	Risk of aggressive groundwater, bolts past design life, maintenance programme	Budget
<b>Construction issue(s)</b>	Sprayed concrete to ISO 9000/14000 with certified operatives	Sprayed concrete to ISO 9000/14000	Sprayed concrete to ISO 9000/14000
<b>Maintenance issue(s)</b>	Maintenance programme	No rock mapping, maintenance programme	If identified, Geotechnical Audit carried out every 2 years, low budget
<b>Monitoring issue(s)</b>	Visual inspection to confirm modelled rock	Bolts catalogued and numbered, long term records kept	Monitoring data of variable quality and content

Tunnel instability is built up from a number of factors that slowly affect a tunnel until a point where a failure occurs and it can be seen within the case studies that the first signs of instability can be relatively minor failures without injury to personnel. However these minor failures can be viewed as a precursor to larger instability problems: for example Case Study D are in the middle of an extensive stabilisation program which started from a single failed bolt head.

The third objective set was to establish what consultants look for when they inspect tunnels prior to designing a stabilisation system. The geological inspection should be carried out prior to anything else and the rock behavior should be predicted based on the geological conditions found on site. Experienced geological engineers can identify hazardous areas that will have a direct impact on operatives that are using the tunnel. How these hazardous areas are dealt with

then ties back into the design life of the tunnel, specific industry regulations (e.g. Quarry Regulations noted at Case Study site G) and the financial constraints of the tunnel owner. The findings of the geological inspection should be appropriately logged and recorded for future reference, it is important to remember that a tunnels design life can change with circumstance, should this happen improved levels of stabilisation must be a consideration in which case the Geological Inspection would need to be reviewed in order to facilitate a more robust design.

The fourth objective was to establish if anything can be done to improve the process of designing and installing a stabilisation system. All interviewees agreed that the use of stainless steel bolts on their sites allowed a reduction in site supervision as there was a lesser need for quality control during installation. The use of stainless steel bolts also meant there were no issues with the handling/storage of bolts on site or a chance of damaging any corrosion protection that has been applied. The good practice noted at Case Study G site: labelling and cataloguing rockbolts and updating these records after each inspection, appears to have contributed towards developing of a maintenance strategy and programme but also guarded against budgetary constraints. Similarly, the NDT and corrosivity testing carried out at two of the three case study sites, despite requiring upfront investment, appeared to have contributed to lowering the overall costs of design, construction, and management of the instability in terms of more precise and accurate risk identification and management which informed the design and, ultimately, construction of the stabilisation options. In this respect, the Ultrasonic, Radio Frequency, Hardness and Ground Rock Anchor (GRANIT) NDT at Case Study D site helped in quick and simple determination of the rockbolt length, while the corrosivity tests at Case Study Sites D and G confirmed a potential cause of rockbolt failure. However, the interviewees were adamant, neither of these tests would have been

effective without a visual inspection by a qualified and competent geotechnical engineer.

In terms of sprayed concrete design and assessment, our study confirmed that rock mapping should be done and suitably recorded before the ‘Shortcrete’ application in order to provide a baseline for future risk assessments and maintenance or monitoring operations as in Case Studies C and D. During ‘Shortcrete’ application, it is important that the Nozzleman and the Design Consultant work closely together to ensure a suitable sprayed concrete system is designed. It might be prudent to consider the use of design and build contracts with regards to Sprayed Concrete projects as this then forces the designer and contractor to work together as they are effectively in the same “team” from a contractual and design risk point of view. The Sprayed Concrete Association do run an accreditation scheme for Sprayed Concrete Nozzlemen however the knowledge of the scheme does not seem recognized in industry. We believe the merits of an accreditation scheme are well founded especially considering the risks associated with incorrectly applied sprayed concrete.

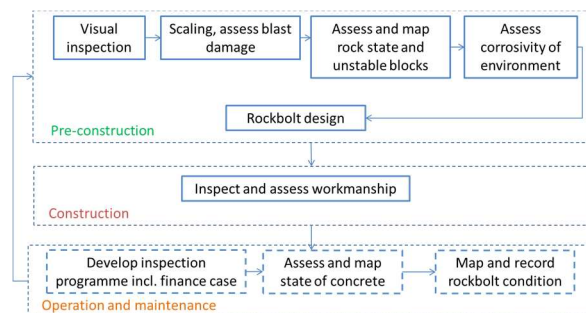


Figure 2. Proposed practical methodological framework for the design and management of instability in hard rock tunnels.

The use of systems such as Lidar technology, noted at Case Study site G, is going to become a larger part of the process, as costs come down and technology develops, and this can only improve the design process for stabilisation systems as it will provide the design engineer with more

accurate information while not exposing surveyors to unnecessary risks during inspection. Similarly, monitoring systems such as the one employed at Case Study site D, combined with detailed record-keeping, can contribute towards leaner design, potentially based on the Observational Method (Spross and Johansson, 2017), and supersede the existing design systems (RMR and Q) which were found deficient at Case Study site G. However, regardless of technology used it is the designers' evaluation of the information that governs the stabilisation system implemented therefore tunnel owners will always continue to rely on the competence of their design engineers to ensure suitable stabilisation systems are installed.

Based on the points above, a practical methodological framework for the design and management of instability in hard rock tunnels can be proposed (Figure 1). The framework is generic enough to allow for consideration of site specific features, although it is biased towards drill-and-blast tunnels where rockbolts and sprayed concrete are used for stabilisation. The tools available to the geotechnical engineer in order to combat tunnel instability will be dependent on the analysis of these features as well as on the required design life of the tunnel and the financial constraints of the tunnel owner. Although our research was limited to a number of representative case study sites and issues in Scotland and Wales, the following industry recommendations can be derived:

a) Regardless of design life or budgetary constraints, a full site geological investigation must be carried out prior to design of any stabilisation system, this should include a full appraisal of existing stabilisation systems already in place. The results of this investigation should be logged and kept for future reference;

b) If clients have the financial capabilities then the choice of stainless steel rockbolts provides high levels of confidence and should be considered. However if stainless steel is not an option then a corrosivity test of the groundwater

should be undertaken so that the correct level of corrosion protection can be applied;

c) The Sprayed Concrete Accreditation Scheme must raise its profile so that it is recognized throughout industry. Perhaps a simple logbook style system could be adopted similar to IRATA Rope Access accreditations where operatives maintain log books of their sprayed concrete experiences and once a suitable level of experience is attained they could then apply for an increased level of Nozzlemen Certification level 1,2,3 etc. This would give engineers a simple method to assess the competence levels of Sprayed Concrete Nozzlemen; and

d) Events of tunnel instability should be logged with date, exact location and nature of the failure, this should occur regardless of severity in order for suitable investigations to be undertaken so that larger failures can be avoided.

In the future, it would be beneficial to carry out a comparison of the case studies presented here with others where the Client does not have the same/similar financial backing but does own and manage a tunnel that requires a substantial design life. This would allow for a better insight in the spectrum of asset conditions and more even comparison across the industry to be made.

## 5 ACKNOWLEDGEMENTS

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